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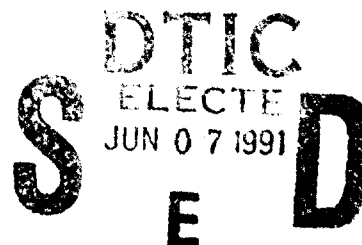
Technical Memorandum

January 1991

Design and Performance of Advanced Blading for a High-Speed HP Compressor

by

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R O Y A L A E R O S P A C E E S T A B L I S H M E N T

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DESIGN AND PERFORMANCE OF ADVANCED BLADING FOR A HIGH-SPEED HP COMPRESSOR

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SUMMARY

A set of advanced blading has been designed for a 5-stage high-speed research core compressor. The blade profiles were aerodynamically-tailored using a sophisticated quasi-3D S1-S2 flow calculation system which was developed at RAF Pyestock. This system involves iteration between blade-to-blade calculations using an inviscid-viscous code, and a streamline-curvature calculation for the pitchwise-averaged throughflow. The design and measured performance of the new compressor are compared with an initial conventionally-bladed 4-stage version. The new design achieved a peak level of polytropic efficiency approaching 91%, a substantial improvement on the initial version, but showed a shortfall in pressure ratio compared with design intent. Post-test analyses based on measured performance data are used to give further insight into this result and indicate possible improvements in the design approach.

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Design and performance of advanced blading
for a high-speed HP compressor

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ABSTRACT

A set of advanced blading has been designed for a 5-stage high-speed research core compressor. The blade profiles were aerodynamically-tailored using a sophisticated quasi-3D S1-S2 flow calculation system which was developed at RAE Pyestock. This system involves iteration between blade-to-blade calculations using an inviscid-viscous code, and a streamline-curvature calculation for the pitchwise-averaged throughflow. The design and measured performance of the new compressor are compared with an initial conventionally-bladed 4-stage version. The new design achieved a peak level of polytropic efficiency approaching 91%, a substantial improvement on the initial version, but showed a shortfall in pressure ratio compared with design intent. Post-test analyses based on measured performance data are used to give further insight into this result and indicate possible improvements in the design approach.

INTRODUCTION

The main aim of the compressor research programme at RAE Pyestock is to develop improved aerodynamic design and analysis methods for axial-flow compressors, so that higher levels of performance can reliably be achieved. This methods development is complemented by a sequence of compressor design, manufacture, test and analysis; improved designs can then be produced and the sequence repeated. For core compressors, the process is centred around a high-speed multistage axial research unit of high aerodynamic loading, designated C147. The initial 4-stage build of C147, which was a conventional design with a design pressure ratio of 4.0, has been described previously (Calvert et al, 1989). This paper extends the discussion to the second build, which incorporates an additional front stage to raise the design pressure ratio to 6.4, and features completely redesigned blading with aerodynamically-tailored blade profiles. The design of the blade profiles, including estimation of profile loss and deviation, depended upon computations of the internal flow, rather than relying on blading correlations. A sophisticated S1-S2 calculation system developed at RAE Pyestock was used

for the flow calculations. The degree to which the design depended upon these calculations, and the application to a relevant, high-speed, highly-loaded multistage compressor are key features of the current work.

The paper first summarizes the main features of C147 and then describes the S1-S2 flow calculation system used for the blading of the second build. The design approach is described in detail, an example of blade profile shapes and blade-to-blade flow predictions is given, and the loss reduction mechanisms are discussed. The overall performance achieved on test indicated substantial improvements in efficiency relative to the first build, with a peak polytropic level at design speed approaching 91%, but a shortfall in pressure ratio compared with design intent. Finally, some post-test analyses are presented, and possible improvements in the design approach and in the flow calculation methods are discussed.

MAIN FEATURES OF C147

The principal design parameters for the 4 and 5-stage configurations of C147 are specified in Table 1. It can be seen that the levels of exit Mach number, hub speed and hub/tip ratio are within current engine limits. Therefore the increased duty of C147 relative to current production engine compressors has to be achieved by higher aerodynamic loading. The initial design of C147 described by Calvert et al (1989) included both 4 and 5-stage versions, but only the 4-stage version was manufactured and tested as build 1. The completely rebled build 2 incorporated the additional zero stage (stages are numbered 0 to 4).

A sectional drawing of the C147 compressor is shown in Fig 1. The unit is much larger than typical engine HP compressors (typically twice linear scale) with larger-than-usual axial gaps (23 mm or about 50% chord) to enable extensive instrumentation to be inserted with minimal disruption to the flow. The rig has provision for aerodynamic traversing in the inter-row gaps and the casing has provision for laser windows. Chordal Reynolds number for the zero stage rotor at the design, atmospheric inlet condition is about 1.1×10^6 . Measured mean rotor clearances for both builds were just over 1% of blade height at design speed.

TABLE 1 OVERALL DESIGN PARAMETERS

	4-stage	5-stage
Pressure ratio	4.0	6.4
Mass flow (at 288K and 1 atm inlet)	33.2 kg/s (73.2 lb/s)	49.5 kg/s (109.2 lb/s)
Rotational speed (at 288K inlet)	6380 rpm	6894 rpm
Exit Mach number (metal annulus)	0.265	0.265
Exit hub speed when operated at 840K delivery temperature	360 m/s (1182 ft/s)	360 m/s (1182 ft/s)
Exit hub/tip ratio	0.912	0.912
Exit blade height	38.1 mm (1.5 in)	38.1mm (1.5 in)
Inlet tip diameter	0.892 m (35.1 in)	0.917 m (36.1 in)
Inlet hub/tip ratio	0.821	0.742

S1-S2 FLOW CALCULATION SYSTEM

General description

Considerable effort has been devoted at RAE Pyestock over recent years to the development and validation of an S1-S2 calculation system capable of predicting the overall and blade row performance and internal flow of a wide range of compressors, and of being used as a design tool. This system was a vital element in the design of the rebladed 5-stage version of C147, and has also been applied to both builds in a post-test analysis mode to aid understanding of the measured results, and to provide a common basis for comparing the two versions. The S1-S2 system involves iteration between blade-to-blade (S1) calculations using the S1BYL2 inviscid-viscous code (Calvert, 1982) and a streamline-curvature (S2) calculation (Ginder, 1984) for the pitchwise-averaged flow. Compared with 3D viscous methods, which in principle offer better modelling of the flow physics, the S1-S2 approach is computationally economical, more thoroughly validated and by its nature particularly well suited to blade profile design improvement.

The blade-to-blade code models the blade surface boundary layers and wake by an integral treatment involving laminar and turbulent regions with instantaneous transition between. The method predicts blade section deviation angle, profile and shock loss in addition to details of the flow field. Experience indicates that predictions are generally reliable for blade sections operating near optimum incidence, but that the significant increase in loss which occurs as the incidence angle increases and the section stalls is not automatically predicted (Calvert, 1983). This is thought to be because the calculation

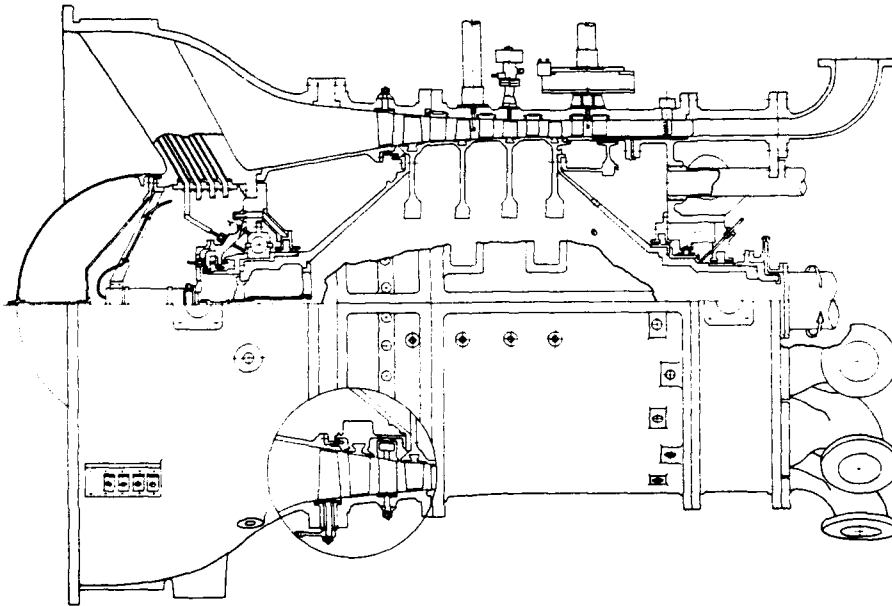


Fig 1 C147 COMPRESSOR

cannot resolve the laminar boundary layer separation and the subsequent reattachment as a turbulent layer which occurs close to the leading edge at high incidences. Such operating conditions can be identified by examination of the blade surface inviscid Mach number distribution - when the maximum loading on the section is predicted to be at or near the leading edge, the section is likely to have a significant leading edge separation bubble. Under these circumstances, the user can specify that the blade suction surface boundary layer should start as a turbulent layer with a given value of momentum thickness Reynolds number (Re_θ). This, admittedly crude, artifice allows predictions to be obtained of the blade row performance as it approaches stall. However, this device is of limited applicability because results depend critically on the choice of starting condition for the boundary layer calculation, and no clear guidelines for the choice yet exist.

For calculating the S2 flow-field in multistage core compressors, a streamline-curvature method is employed. This is a simplified version of that described by Ginder (1984) and is run in a 'ductflow' mode, with calculating planes placed at the blade leading and trailing edges only. Linear variations of stream-surface radius and stream-tube thickness are assumed within the blade rows for the S1 calculations. The blade performance data, consisting of exit flow angle, profile and shock loss coefficients, are derived from the S1 solutions via a wake mixing calculation carried out on the downstream boundary of the S1 domain.

End losses, arising from secondary flows, annulus wall boundary layers and tip clearance, are not predicted from the S1-S2 treatment currently adopted. Therefore appropriate radial distributions of extra loss must be specified as an input. This loss, together with annulus blockage, represents the only empirical input required to the S1-S2 calculation system. However additional empirical input eg deviation corrections, can be included where necessary; for example in post-test analysis to match S1-S2 solutions more closely with test measurements.

Appropriate distributions of annulus blockage and blade end loss have been determined from analysis of a number of multistage compressors at RAE. End losses are assumed to be proportional to the mean profile loss of the blade row in question and, since the S2 calculation does not include a spanwise mixing mechanism, these are spread across the whole span (using a parabolic distribution). The resultant total loss coefficients are typically twice profile loss at mid-span, and rise by about 65% towards the blade ends. A blockage allowance which increases by 1% per blade row is generally appropriate, with the inlet blockage being chosen according to the particular test installation. For C147 a blockage value of 2% is adopted at inlet to the first rotor, increasing over the first 4 stages and then remaining constant.

The SIBYL2 calculations, which are carried out on a sheared H-grid, adopt uniform axial and tangential spacing within the bladed region, generally with 51 axial and 16 or 21 tangential points; further points are used to extend the calculation domain by about 0.8 axial chords upstream and downstream. The gas specific heats are set to average values for each blade row according to local conditions. The turbulence levels assumed correspond to an inlet relative value of 5% throughout the machine. In the S2 calculation eleven quasi-streamlines are employed, equally spaced across the annulus height. The calculating planes are leaned (non-radial) but straight and positioned to give a close fit to blade leading and trailing edges throughout the machine.

When applied to build 1 of C147 in a post-test analysis mode (Calvert et al, 1989), the S1-S2 system gave encouraging agreement with the measured overall and stage performance, but did not give a good match to the radial profiles obtained from aerodynamic traverse measurements at stage exits. The predicted total pressure profiles were fairly flat whereas the measurements revealed significant radial variations in both the end-wall and mainstream regions. In the predictions the radial

profiles and absolute levels of stage efficiency remained broadly similar throughout the machine, in line with the simple loss model used. In contrast, the traverse measurements indicated that stage efficiency levels fell through the machine and that there was a progressive change in the shape of radial profiles, from a profile for stage 1 which showed losses to be concentrated near the end walls, to much flatter profiles in the rear stages. This effect is consistent with the impact of spanwise mixing, which progressively distributes the end-wall losses across the blade span, and eventually leads to the 'repeating stage' situation.

It was concluded that the addition of a mixing mechanism to the S1-S2 system was needed to improve the prediction of the radial variation of flow parameters. However, examination of the detailed blade-to-blade results indicated that there was considerable scope for improving the aerodynamic performance of the circular-arc profiles used on build 1. Worthwhile increases in the already-high levels of efficiency appeared feasible. It was thus decided to undertake a blade profile redesign exercise using the current familiar system, prior to the development of improved flow modelling.

DESIGN PARAMETERS

Stage parameters

The stagewise distributions of V_a/U (axial velocity/mean blade speed), $\Delta H/U^2$ (enthalpy rise/mean blade speed squared) and pressure ratio given by Calvert et al (1989) were retained for build 2. However, the reaction distribution was changed. For the initial design, stage inlet flow angles for the front stages were kept low to limit stator hub Mach numbers to about 0.8. Inlet flow angles for the rear stages were increased in order to reduce the stator duties, and to balance inlet Mach numbers and flow deflections for rotors and stators. The resultant stage inlet flow angles were 7.5°, 10°, 13.5°, 17° and 24.5° for stages 0 to 4 respectively. The swirl at exit from stator 4 was 38°, and this was removed by an extra outlet guide vane row. In the rebladed version, it was found that increasing the pre-swirl to 12.5° in the front stages eased the rotor design without significant penalty to the stators. By maintaining this level of swirl throughout the machine, and allowing 5° of residual swirl at delivery, the need for a double stator row at exit was removed.

A remotely-variable inlet guide vane was specified for the 5-stage version to enable the axial mismatching at part speed to be reduced. The IGV and stators are cantilevered and unshrouded, apart from stator 0.

Blading parameters

The two designs differed significantly in the methods used to estimate loss and deviation. The initial design used blading correlations, whereas for build 2 the deviation and profile loss were based on SIBYL2 predictions, with extra losses derived from a rule similar to that described earlier. In both cases the levels of loss coefficient thus estimated were felt to be rather optimistic, and were increased slightly to accord with reasonable target values of design point efficiency. For build 2 the target value was 90% polytropic and for build 1 it was 88% polytropic. For both designs, the radial variations of loss were similar and the radial distributions of work were chosen to produce flat radial profiles of total pressure at exit from each stage.

A further important difference between the build 1 and build 2 designs concerns the types of blade profile used. For build 1, the profiles had circular-arc camberlines throughout, with double-circular-arc thickness distributions being used for most rows. Choice of blade incidence and space/chord ratio was guided by choke and stall margin correlations. On build 2 the blade profiles were of more general form and little guidance was available from blading correlations. This meant that much reliance was placed on the aerodynamic judgement of the designer, guided by the SIBYL2 predictions.

DETAILED DESIGN OF BUILD 2

Blading approach

The blade profiles used for rotors and stators were set up using a geometric generator developed at RAE which has been described by Calvert, Ginder and Lewis (1987). Up to 4 circular arcs can be used to define the suction surface and the fourth arc can be parabolic if required. On C147 the full freedom given by this generator was not required, and profiles with suction surfaces made up of 2 or 3 circular arcs were adopted for stages 0 to 2, while profiles with single parabolic-arc suction surfaces were used for stages 3 and 4. All rotors and stators had pressure surfaces made up of two cubics, with continuous slope and curvature at the junction.

The blade profile shapes at several spanwise positions on each blade row were developed in a process of iterative refinement using the S1BYL2 blade-to-blade code. Particular attention was paid to the behaviour of the suction surface boundary layer. Low values of profile and shock loss were sought, while avoiding extremes which might be over-sensitive, either to the accuracy of the prediction method or to the precise operating condition. Space/chord ratios were kept close to those of the initial design for the first 3 stages, but higher rotor values and lower stator values were needed in the rear stages because of the change in reaction. Thickness/chord ratios of rotors 0 to 3 and stator 0 were the same as on build 1, other rows were slightly thinner. Apart from the outer region of rotors 0-2, where shock effects were of some concern, and suction surface camber in the uncovered region had to be limited, the blade profiles were more forward-loaded than for the initial design. The proportion of camber in the first half of chord was considerably greater than with circular-arc profiles, especially in the rear stages. The predicted reductions in loss were encouraging, typically profile loss coefficients were 25-30% lower than for circular-arc profiles.

Off-design considerations

Although only a single design point was used, the blading design for build 2 of C147 paid consideration to off-design performance in several ways, for example in the selection of camber distribution and in the choice of conventional space/chord ratios and low effective incidences (as assessed by predicted aerodynamic loading at the leading edge). The design was thus more conservative than would have been the case if the highest predicted level of design point efficiency had been targetted. Furthermore, the definition of the blading for stages 3 and 4 took account of additional S1BYL2 predictions which were carried out at incidences 4° greater than the design value and with fully turbulent suction surface boundary layers. These computations influenced the choice of parabolic-arc suction surfaces for the last 4 rows.

The choke margins of the new blading at design point were estimated from the predicted mean passage entry Mach numbers, and found to be very similar to those of the initial design.

Example of blade-to-blade aerodynamics

A useful way of illustrating the predicted improvements in blade-to-blade aerodynamics is to compare a parabolic-arc profile of the type used for the rear rows of build 2 with a circular-arc profile of the same space/chord, thickness/chord and flow turning, operating at the same inlet conditions. The duty is close to that of stator 3 at mid-height, both sections are set at zero effective incidence (which is a little lower than typical for build 2) and for simplicity they have constant stream-surface radius, with no stream-tube contraction or extra loss. The results of the S1BYL2 predictions are shown in Fig 2; these include Mach number variations in the inviscid flow-field and integral parameters of the blade boundary layers. It can be seen that the high forward camber of the

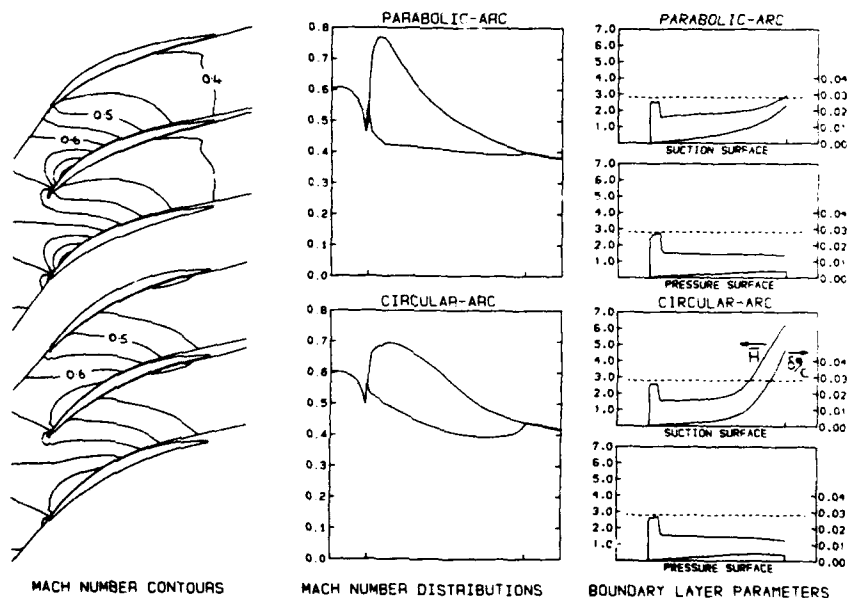


Fig 2 PERFORMANCE PREDICTIONS FOR PARABOLIC AND CIRCULAR-ARC PROFILES

parabolic profile (which has a 3.5 to 1 variation in curvature along the suction surface) causes a more rapid and more persistent acceleration on the initial part of the suction surface compared with the circular arc case, and the peak Mach number is almost 0.1 higher. This high peak is immediately followed by a diffusion rate which is initially much steeper than for the circular-arc case, but becomes progressively less severe in the covered passage and towards the trailing edge. The transition point is not significantly affected, remaining near 10% axial chord, but the greatest loading on the suction surface boundary layer now occurs much further forward - near the front of the covered passage, where the layer is thin and better able to withstand it. By this means, the boundary layer separation evident near 75% of axial chord for the circular-arc case (which is apparent from the rapid increase in displacement thickness δ^* and in shape factor H ¹ through and beyond its nominal 'separation' value of 2.8) is almost entirely avoided. Values of δ^* and H at the trailing edge are roughly halved, and the predicted mixed-out profile loss coefficient is reduced by about 30%.

Even greater predicted loss reductions could have been achieved by designing for yet higher initial diffusion rates, graduating to very low rates towards the trailing edge - an approach associated with 'supercritical' profiles. However this would lead to higher values of shape factor and displacement thickness in the mid-chord region. While this feature may not be of obvious concern near design incidence, it could become critical at high incidences, leading to early separation and resultant loss of operating range.

Loss generation

Some insight into loss generation and reduction can be gained from comparing predicted values of momentum thickness for the two profiles discussed above. At the downstream boundary of the calculation domain, the wake momentum thicknesses for the two cases are, as might be expected, roughly proportional to their profile loss coefficients (ie differing by 30%). However, near the trailing edge the two cases have very similar values of (combined suction and pressure surface) momentum thickness - in broad terms viscous losses generated over the blade surfaces appear to be similar. Downstream, the momentum thickness for the circular-arc case increases by some 80% in the wake region, compared with about 30% for the parabolic case. Such increases in momentum thickness are at first sight surprising, but do appear to be broadly consistent with the momentum integral relationship. In simple terms, this relates the rate of change in momentum deficit in the wake to the product of displacement thickness and pressure gradient. In the present case considerable viscous blockage is generated at the blade trailing edge plane (10% of pitch for the circular-arc case), and this causes an adverse pressure gradient as it decays downstream within the S1 streamtube, which has constant thickness and is at constant radius. The predicted values of blockage and pressure gradient and the predicted changes in momentum thickness appear to be consistent.

While neither the SIBYL2 wake treatment nor the current analysis are exact, the results do appear to indicate that (for circular-arc aerofoils in highly-loaded turbomachinery at least) a significant proportion of the predicted profile loss is generated during mixing of the broad wake. Most of the improvement predicted for the build 2 design arises from reduced levels of mixing loss, due to the thinner and almost unseparated trailing edge boundary layers. These conclusions are backed by more rigorous analyses in which entropy or energy thicknesses are considered in place of momentum thickness.

¹ H is effectively the shape factor (ratio of displacement to momentum thicknesses) of an equivalent incompressible boundary layer.

The above indications appear contrary to some conclusions reached by Denton and Cumpsty (1987) in their discussion of loss mechanisms in turbomachinery. Denton and Cumpsty rightly point out the potential importance of the entropy generated during wake mixing and, as an example, estimate that with 'conventional' (well-attached) turbulent boundary layers near a blade trailing edge, about 15% of the total entropy production occurs during mixing. They also point out that this proportion could be substantially greater if the boundary layer near the trailing edge is separated, and if the wake mixing occurs in a diffusing flow (which is the case here, as mentioned above). However, they also suggest that separated flows at a trailing edge may be treated as increased trailing edge thickness with an appropriate base pressure. For a 'small' separated region at the trailing edge causing 10% blockage (close to the value predicted for the current circular-arc case), a mixing loss of 0.01 of exit dynamic head would be generated. This is quite small, corresponding typically to a loss coefficient of less than 0.005 based on inlet dynamic head (compared with the total value of 0.04 predicted here by SIBYL2). Denton and Cumpsty conclude that double-circular-arc blades which show such separations are quite efficient, benefiting in particular from the comparatively low values of peak suction surface velocity. (Peak velocity is important because of the dependence of local entropy production rates on the third power of free stream velocity). In contrast the current SIBYL2 predictions indicate that regions of separated flow and the consequent mixing losses carry much greater weight, and that eliminating them can give significant profile loss reductions in spite of higher peak velocities. The test results for build 2 of C147 verify the effectiveness of this approach, and the traverse results shown later are good evidence that blade wakes are in reality substantially narrower than for circular-arc blades.

The C147 test results cannot, of course, verify the SIBYL2 predictions in detail. While SIBYL2 has proved reliable in many applications, details of the loss evolution have not been verified, and the method does contain approximations. For example, the treatment of the wake development is not exact, and the boundary layer calculation uses empirical correlations which are based mainly upon data obtained at higher Reynolds numbers. With these uncertainties in mind, it would be valuable to make comparisons of predicted loss evolution with other flow calculation methods, particularly Navier-Stokes solvers, and with experimental evidence. In this respect it is interesting that predictions for the double-circular-arc V2 stator cascade using a Navier-Stokes code (Dawes, 1988) show relatively little mixing loss, even though substantial flow separations are known to occur for this case. In a more general analysis, Dawes (1990) attributes most of the loss production to the region deep within the boundary layer, with the part of the blade surface near the peak velocity point being the major contributor because of the previously-mentioned dependence on free stream velocity. Further work is clearly needed to resolve the apparent discrepancies between the current findings and those in the references cited. Such work would be valuable in increasing understanding of the mechanisms of loss generation and reduction.

MEASURED COMPRESSOR PERFORMANCE

Information on the test installation and instrumentation of C147 is given by Calvert et al (1989). The overall characteristics given in Fig 3 show that the 4-stage initial build exceeded its design-target flow and pressure ratio, each by about 3%, and achieved a very respectable peak polytropic efficiency level of just over 89% at a surge margin of 15%². At 25% surge margin the polytropic efficiency was just under 87%.

² Surge margin is expressed as $(R_{\text{surge}} - R) / (R - 1) \times 100\%$ where all pressure ratios, R , are measured at the same mass flow.

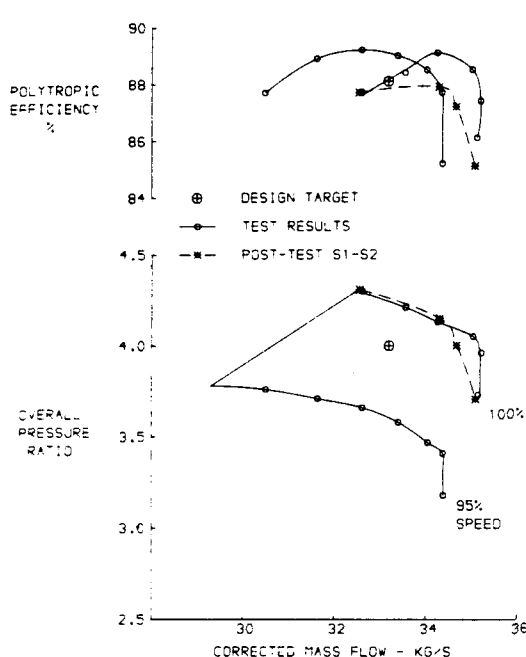


Fig 3 OVERALL PERFORMANCE OF C147 BUILD 1

The overall performance of the 5-stage build 2, measured at 90%, 95% and 100% of design speed, is shown in Fig 4. Nominal inlet conditions were 0.9, 0.8 and 0.7 bar at 90%, 95% and 100% speeds respectively, and the IGV was closed by 10° from its datum setting at 90% speed and by 5° at 95% speed. Notable features of build 2 are the wide flow range, which is similar to that achieved by build 1, and the flat pressure ratio characteristics above peak efficiency, particularly at design speed.

Build 2 achieved a peak efficiency level at design speed over 90%, some 1% greater than for build 1, but the peak efficiency point was 1% low on flow and 6% low on pressure ratio compared with design intent. The maximum flow passed just equalled the design value. The surge line shown on Fig 4 corresponds to a surge margin of about 10% at the design speed peak efficiency point. Efficiency remains high at 25% surge margin, the polytropic value being just over 89% - over 2% greater than the corresponding value for build 1. However the pressure ratio at this operating condition is only 5.5, compared with a value of about 5.9 which would have been reached if the design point had been achieved with a nominal 10% surge margin. The performance at 95% speed is worthy of note, with a peak efficiency level close to 91% polytropic being achieved in conjunction with a surge margin of 23%.

The very high levels of efficiency achieved by build 2 of C147 are extremely encouraging, and underline the potential of the design approach adopted. The deficit in pressure ratio is disappointing, and would obviously be of concern for a project compressor. However, the stage matching appears to be good

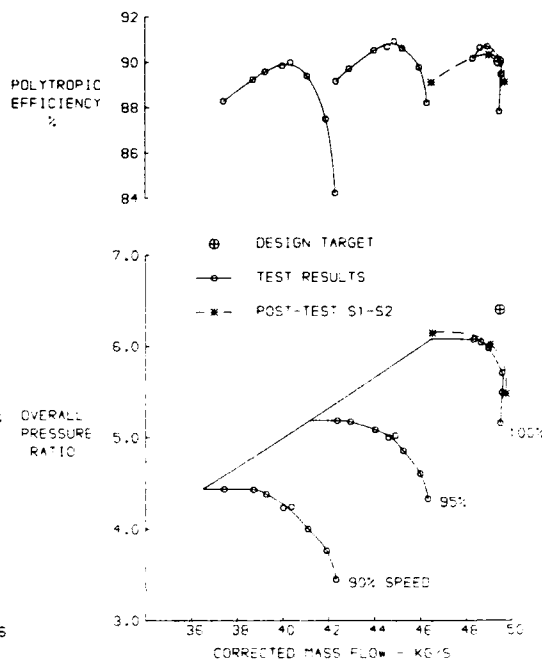


Fig 4 OVERALL PERFORMANCE OF C147 BUILD 2

and the deficit does not substantially detract from the value of build 2 as a research vehicle. Obviously the reasons for the deficit must be understood as part of the continuing process of improving the design methods.

Analysis of the aerodynamic traverse measurements, obtained using both conventional steady-state and high-response instrumentation as well as laser anemometry, is in hand. As an example of the data available, contour plots of absolute total pressure measured at the exit of stator 2 at the peak efficiency operating condition at 100% speed are shown in Fig 5, for both builds of C147. These data are not corrected for the differing inlet conditions. The results provide confirmation of the narrow wakes and reduced viscous losses predicted for build 2.

POST-TEST S1-S2 ANALYSES

On build 1, a good prediction of the overall performance near the peak efficiency operating point (apart from a 1% underprediction of efficiency) was achieved without any adjustments to the parameters of the S1-S2 system, as can be seen in Fig 3. For build 2, some adjustment was needed to cater for the shortfall in pressure ratio. Following examination of the measured and design-intent stage performance, which indicated that no particular stage or group of stages was responsible for the deficit, it was decided to incorporate a 1° deviation correction on every blade row. A correction of this magnitude is within the uncertainty band of S1BYL2 predictions (Calvert, 1983) and of most blading correlations.

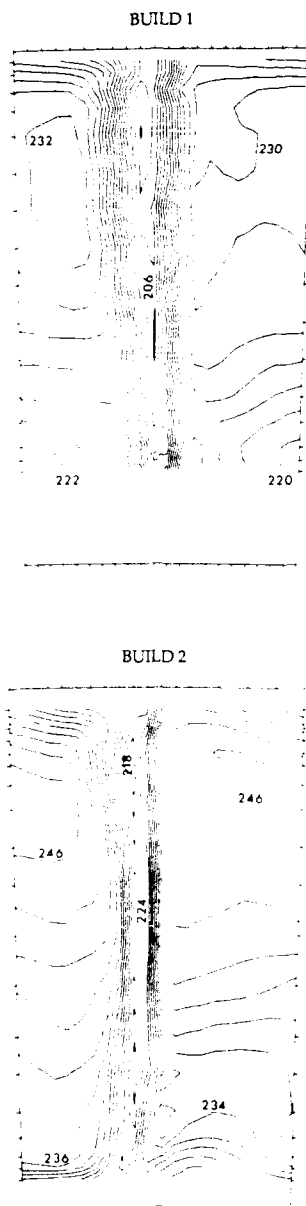


Fig 5 TOTAL PRESSURE TRAVERSES AT STATOR 2 EXIT (KPa)

The overall performance after this adjustment, predicted by an S1-S2 solution set up at the test inlet condition of 0.7 bar and near the peak efficiency operating point, achieves a close match to measurement, as can be seen in Fig 4. The change in inlet condition from the design value of 1 bar is significant - other S1-S2 analyses indicate that the change in Reynolds number affects the pressure ratio by about 2% and the efficiency by about 1%. Because the predicted pressure ratio is very sensitive to the assumed value of mass flow, individual solutions can be misleading and so further S1-S2 solutions have been produced to match the measured pressure ratio characteristics over the full flow range. Similar solutions have been produced for build 1. To model operating conditions close to surge, further empirical adjustments were needed for both builds, specifically concerning the selection of starting conditions for the suction surface boundary layer calculations.

Examination of the predictions in detail shows that both builds have good axial and radial matching at the peak efficiency analysis points, with the blading generally operating at low, positive effective incidence. Suction surface boundary layer transition occurs at about 5-10% chord. On build 1 fairly rapid growth of the boundary layer occurs typically from about 60% axial chord, followed by separation beyond 75% chord, as might be expected for highly-loaded circular-arc blade sections. On build 2 this separation is largely eliminated. Compared with build 1, build 2 displays similar or lower peak Mach numbers in the front rows but rather higher peak values in the rear rows, as expected from the example given earlier. However peak Mach numbers are generally subsonic, apart from rotors 0 and 1 where the values are between 1.1 and 1.25. Shock loss is of little concern, but some shock/boundary layer interaction is present.

For build 1 the prediction near surge, which was carried out at the measured surge exit flow function, achieves an acceptable match to the measured overall performance if fully turbulent suction surface boundary layers are assumed on all blade rows, starting from a specified value of momentum thickness Reynolds number, Re_{θ} , of 100 at the leading edge.

The use of fully turbulent layers is consistent with the high incidences apparent in the blade-to-blade solutions, which show maximum loading at the leading edge throughout the compressor, accompanied by spikes in the Mach number distribution on several rows. The use of tripping is preferred to arbitrary adjustments in loss, deviation and annulus blockage because it enables the blade aerodynamics to be more representative of the situation caused by the local separation at the leading edge, which is thought to occur at high incidences, as mentioned earlier. While the value of Re_{θ} assumed at the leading edge is artificial, being lower than the minimum value of about 300 usually associated with turbulent boundary layers, it rises rapidly to more normal levels.

In general, tripping does not have a serious effect on boundary layer development for build 1. The suction surface layers remain under control for much of the chord, and separation only moves upstream by 5-10% of chord compared with the maximum efficiency analysis point. Deviations are typically $\frac{1}{2}^{\circ}$ to 1° higher and profile losses 10% greater, due to the combined effects of tripping and the incidence change of about $2\frac{1}{2}^{\circ}$. While these effects may appear modest, they have considerable influence on the shape of the predicted overall characteristic, as can be seen by comparing the surge result with the trend of the other solutions in Fig 3 (which are all untripped).

The surge solution obtained for build 2 was again at a value of exit flow function close to measurement. In this case the changes in incidence from the peak efficiency analysis point are rather less than on build 1, and the effective incidences are lower. Only the first few rows show peak loading at the leading edge. It was thus somewhat surprising that a more severe tripping assumption was needed than on build 1, in order to give reasonable agreement with measured overall performance. An Re_{θ} value of 150 was needed compared with

100 previously, in addition to the deviation correction mentioned above. This increase in Re_θ has a significant effect on the predicted blade aerodynamics and these are now in a more critical state than on build 1 near surge, particularly for the middle stator rows, where extensive regions of separated flow are apparent. Rotor 0 is also in trouble, due to interaction between the shock wave and the artificially-thickened suction surface boundary layer. The increases in profile loss compared with the peak efficiency analysis point are greater than the average value of 10% observed on build 1, and amount to 20-40% for rotor 0 and the stator rows, where they are accompanied by changes in deviation of around 1°.

Further studies have shown that some refinement of blade profile shapes and reduction in space/chord ratios, particularly for the middle stator rows, would improve the situation to some extent. However, in order to make a substantial improvement, it appears that blade profiles of the type adopted should be set at lower effective incidences than corresponding circular-arc profiles, to compensate for the more rapid performance deterioration with increasing incidence.

It would of course be dangerous to over-interpret the S1-S2 solutions, bearing in mind their previously-mentioned shortcomings. However these solutions, particularly when applied in a post-test analysis mode, do appear capable of giving useful insights into aerodynamic behaviour over a range of operating conditions and are of value in compressor development. Off-design S1-S2 predictions are now used as an integral part of the design process. This is especially important for an engine application where a specified surge margin target has to be met. With this approach, together with the use of a deviation correction and allowance for the sub-atmospheric inlet condition, it is anticipated that design-intent pressure ratio and an increased surge margin could be achieved in a redesign of build 2 without substantial penalty in efficiency.

The above measures permit improved designs to be produced with the current S1-S2 system. However it is highly desirable to develop the system further so that measured performance characteristics can be predicted without empirical adjustments. The analyses discussed above focus attention on improving the S1 treatment to increase accuracy at off-design conditions, and to avoid the need for deviation corrections which vary with blade profile type. Such developments are in hand - although improving the predictive accuracy of the method to better than $\pm 1^\circ$ on deviation will be challenging. As regards the S2 treatment, it is recognised that the known shortcomings in predicting the radial variation in flow parameters may also be a significant factor, and these must also be tackled. Consequently the S2 calculation has now been modified to incorporate a spanwise mixing mechanism, and improved treatment of blade/end wall effects is also in hand.

CONCLUSIONS

A second build of the C147 core research compressor, with advanced blading and an additional zero stage compared with the initial 4-stage version, has been designed and tested at RAE Pyestock. Particular aims were to investigate the performance potential for highly-loaded rear stages of blading with aerodynamically-tailored profiles, and to assess the impact of basing the design on S1-S2 flow calculations, instead of the

blading correlations used previously. The measured performance of the new design was extremely encouraging, with a peak level of polytropic efficiency approaching 91% being achieved at design speed, at a surge margin of 10%. Corrected to a common inlet condition, the peak efficiency level is about 2% higher than for the conventionally-bladed 4-stage initial design. However, the compressor fell substantially short of its design-intent pressure ratio. Post-test S1-S2 analyses at several operating points have been employed to help diagnose this result. Modifications to the design approach are indicated which should enable the shortfall to be recovered without significant penalty elsewhere. In addition, improvements to the S1-S2 flow calculation system are in hand to improve its accuracy, particularly in the blade end regions and at off-design operating conditions. These developments should provide scope for further performance improvements and enable design intent performance (including a target surge margin) to be achieved more closely on first test, as well as allowing more adventurous duties to be tackled.

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17. Abstract A set of advanced blading has been designed for a 5-stage high-speed research core compressor. The blade profiles were aerodynamically-tailored using a sophisticated quasi-3D S1-S2 flow calculation system which was developed at RAE Pyestock. This system involves iteration between blade-to-blade calculations using an inviscid-viscous code, and a streamline-curvature calculation for the pitchwise-averaged throughflow. The design and measured performance of the new compressor are compared with an initial conventionally-bladed 4-stage version. The new design achieved a peak level of polytropic efficiency approaching 91%, a substantial improvement on the initial version, but showed a shortfall in pressure ratio compared with design intent. Post-test analyses based on measured performance data are used to give further insight into this result and indicate possible improvements in the design approach.					

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